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An Experimental Assessment of Waste Transformer Oil and Palm Oil Biodiesel Blended with Diesel Fuel on A Single Cylinder Direct in Diesel Engine

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Abstract— **The present work emphasized overall viability study of using waste transformer oil (WTO) and its combinations on a diesel engine. To accomplish this fuel samples were divided into three sets with different volumetric proportions. Each set of fuel is compared with the others and finally, the reference fuel is regular diesel. After thorough characterization and utilizing spectroscopic methods like CHNS analysis and FTIR, the performance and emission evaluation was done on a one-cylinder diesel engine. It has been discovered that the flash point, calorific value, and viscosity of WTO blends are more than regular diesel fuel. The WTO blends have higher carbon content than diesel but higher Sulphur content than diesel fuel. WTO and its blends have some similar functional groups as diesel fuel. According to the performance and emission evaluation, the diesel engine is capable of operating even when fueled with raw WTO. Among all the samples tested, WTO20 BD10D70 shows the most satisfactory result. The brake thermal efficiency of WTO20BD10D70 was almost similar to diesel fuel, while BSFC and BSEC were found to be only 4.73% and 3.46% higher than diesel fuel, respectively. The exhaust gas temperature was 8% lower than diesel. However, HC emission of WTO20BD10D70 was 20% more than diesel fuel, while CO and NOx emissions were 14% and 4.75% lower than diesel fuel. So, the sample code with WTO20BD10D70 can be recommended as a substitute for regular diesel fuel.**

Keywords— **Engine performance; alternate fuel; emission characteristics; diesel fuel; biodiesel; waste transformer oil.**

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I. INTRODUCTION

The significant and pressing need for alternative fuel sources has arisen due to the enormous demand for transportation and power generation, the rapid exhaustion of fossil reserves and the increasing levels of environmental pollution [1]–[4]. This has sparked substantial interest in the search for alternative fuel sources [5], [6]. As reported in the literature, a large number of alternative fuels are found to be suitable for internal combustion engines such as gaseous fuel [7], [8], pyrolysis oil [9], [10], alcohol [11], [12], hydrogen [13], [14], biodiesel [15], [16], vegetable oil [17], [18], ether [19], [20], and furan [21], [22]. The renewable energy source that is most reminiscent of diesel fuel is biodiesel [23], [24]. Due to its intrinsic oxygen content, biodiesel has various benefits over diesel, including fewer exhaust emissions, better lubricating properties, and non-toxicity [25]–[27]. Waste transformer oil has been considered a possible replacement for diesel engines in these situations [28], [29]. Currently, mixtures of waste transformer oil (WTO) with diesel are used to power engines rather than using WTO.

Numerous experiments have been conducted on biodiesel to turn waste into energy [30], [31]. The Indian economy is rising steadily, and energy demand will be at its highest in the coming decade. Total primary commercial energy consumption is growing at 4% per year, reaching 927 megatons of oil equivalent (MToE) in 2021. Oil consumption has increased steadily over the years; the net consumption increased to 14.4 million metric tonnes (MMT) from 1950 to 1970, then 194 MMT in 2019-20. More than 5% growth is projected in 2022. 2004–05, oil production was 33 MMT. The Biodiesel Society of India was founded by business owners, scientists, officials, and community organizers concerned about diminishing oil sources, rising crude costs, and global warming. Even though WTO's viscosity is nearly three times that of regular diesel at operating temperatures, engines performed better using it [28]. Compared to diesel fuel under full load, the stated HC and CO emissions for a given proportion of WTO and diesel mixes are much more significant [32]. Reports have come out recently saying that biodiesel, made from plant oils, makes diesel engines less powerful [33], [34]. It was found that vegetable oil's high viscosity has some adverse effects on engine power [35], and the transesterification process was proven to be an excellent way to use both edible and non-edible vegetable oils [36], [37]. Alcohol has lower cetane ratings, but it offers advantages like oxygenation and ease of production. Researchers have examined alcohol use with various biodiesels and diesel [38]. Oils made from the pyrolysis of different feedstocks have also been used to fuel CI engines, but they have poor ignition quality, make emissions worse, and cause engine parts to corrode [39]. Waste cooking oil (WCO) has also become a possible source for the third generation of biodiesel, and its blends are where extensive research efforts are dedicated to studying [40], [41]. Several good catalytic and non-catalytic processes have been attempted throughout the years to convert oils into biodiesel [42]. Transesterification, which breaks down lengthy chains of triglycerides into simpler methyl esters like biodiesel, has proven the most successful [43], [44]. A thorough assessment of machine learning technology's use in biodiesel modeling, optimization, and monitoring has also been made, with the recommendation that lab testing come first before commercialization [45]. Biodiesel is identical to petroleum diesel in attributes like combustion heat and octane number [46]. However, when burned, it produces far fewer harmful emissions of particulate matter, carbon monoxide, and sulfur [47]. To make biodiesel, transesterify triacylglycerol or fatty oils using a basic or acidic catalyst. As biodiesel synthesis enters its third generation, alternative approaches such as whole-cell biocatalysts, magnetic-assisted transesterifications, and plasma-assisted transesterifications are emerging as viable substitutes for enzyme-catalyzed transesterification, attracting significant attention from researchers [48]–[51]. Biodiesel feedstocks are undergoing a similar revolution, with a focus shifting to the development of genetically modified plants that can generate more of the highest-quality biodiesel at scale [52]. In the not-too-distant future, it could replace diesel in all diesel engines [53]. Several biodiesels have been shown to have a calorific value that is slightly greater than diesel fuel, while others have been found to have a lower calorific value. Numerous studies have demonstrated that adding 20 percent biodiesel to fuel decreases PM emissions by 22 percent [54].

In the last few years, many researchers have put their efforts into studying the use of biodiesel obtained from the WTO [55][56]. Activated carbon from coconut shells was used as a catalyst in the transesterification process to make biodiesel from WTO, and it was shown that adding 20% WTO biodiesel improved the engine's thermal efficiency and reduced emissions [5]. Catalytically cracked biodiesel blends showed a marked improvement in both brake thermal efficiency and peak heat release rate, which reduced hydrocarbon emissions but increased nitrogen oxide emissions compared to diesel at maximum load conditions [29], [57], [58]. According to the study conducted by [59], the properties of combustion, performance, and emissions of a biodiesel-like fuel obtained from a mixture of WTO and canola oil were analyzed. The results revealed that this fuel demonstrated noticeably higher values of brake-specific fuel consumption, brake thermal efficiency, and exhaust gas temperature than diesel fuel. Based on the available literature, it has been found that there are severe consequences for the environment when used transformer oil is dumped into the ground or the water supply. Avoiding these issues requires recycling the used oil. With research suggesting WTO might be utilized as a diesel alternative, this harmful waste oil must be recycled in an eco-friendly manner. High temperatures and moisture accelerate the deterioration of transformer oil. When exposed to electrical and thermal stresses in an oxidizing environment, transformer oil gradually loses its stability, decomposes, and oxidizes; its acidity rises, and it eventually begins to form sludge [60]. A survey of the relevant literature reveals a paucity of research on the utilization of waste transformer oil (WTO) as a viable alternative fuel for CI engines.

II. Materials and Method

A. Fuel Sample Preparation

Waste transformer oil and palm oil (Biodiesel): Transformer oil and palm oil have been procured from Nav International, Kolkata. The diesel oil is procured from a fuel refilling center at Sindri, Dhanbad. The fuel samples' physicochemical, spectroscopic, performance, and emission characteristics have been studied by categorizing them into three sets. The first set of fuel samples are raw diesel samples, palm oil biodiesel, and waste transformer oil. The second set of fuel samples are the blends of waste transformer oil and diesel. In contrast, the third set of fuel samples consists of the blends of waste transformer oil, palm oil biodiesel, and diesel with different volumetric proportions. The measuring flasks, beakers, and other equipment are handled carefully to prevent any moisture or dirt from getting into the fuel mix. Each fuel sample is then coded accordingly and shown in Table I.

TABLE I
Biodiesel Blends Nomenclature

Sample Labeling	Configuration by Vol (%)
D100	100% Diesel oil
BD100	100% Biodiesel oil
WTO100	100% Waste transformer oil
WTO20D80	20% Waste transformer oil, 80% Diesel oil
WTO30D70	30% Waste transformer oil, 70% Diesel oil
WTO20BD10D70	20% Waste transformer oil, 10% Biodiesel oil, 70% Diesel oil
WTO30BD20D50	30% Waste transformer oil, 20% Biodiesel oil, 50% Diesel oil

B. Test Equipment

Various test equipment, viz., a CHN analyzer, and a Fourier transform infrared spectrophotometer (FTIR) analyzer are used to test the prepared samples. An elemental analyzer (CHN) determines how much carbon, hydrogen, and nitrogen are in organic molecules. It is based on the Dumas method's basic tenets. The CHN device, Fig. 1, is used to test the material at a high concentration level and is manufactured by Thermo Finnigan, Italy. FLASH EA 1112 series model at SAIF, IIT Mumbai. The equipment is calibrated by analyzing a sample chemical and calculating K-factors. This method is most helpful in finding the percentages of carbon (C), hydrogen (H), nitrogen (N), sulfur (S), and oxygen (O) compounds in the samples, which are generally flammable at around 1800oC

Fig. 1 CHN - Elemental analyzer

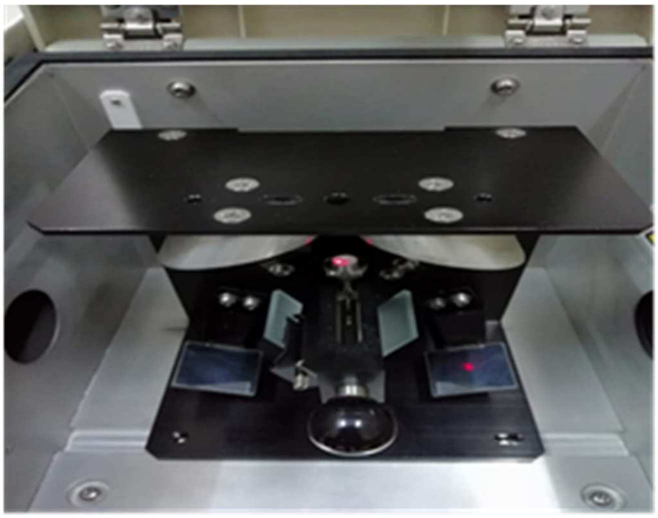


Fig. 2 FTIR Interferometer

Infrared spectroscopy, also called 'vibrational spectroscopy,' incorporates the study of light in the infrared (IR) absorption spectroscopy part of the electromagnetic spectrum, which has a longer wavelength and lower frequency than normal visible light. Here, a variety of approaches co-exists, however, a majority of which are again based on absorption spectroscopy (Fig. 2). This may be used to recognize and analyze compounds, just like any other spectroscopic approach. Infrared spectroscopy produces an infrared spectrum for a particular sample, which may be solid, liquid, or gaseous, using an infrared spectrometer (or spectrophotometer). The infrared spectra of diesel, waste transformer oil, and their blends were recorded in the region of 4000-400 cm^{-1} using an instrument manufactured by Shimadzu Corporation in Japan, which was housed at the Central Instrument Facility (CIF), BIT Mesra Ranchi.

C. Experimentation Setup

This study used a single-cylinder, four-stroke, water-cooled CI engine with a rated output of 5 BHP at 1500 RPM and a dynamometer rope (G.P. Industries, Coimbatore). Table II lists the engine's technical parameters. Fig. 3 depicts the experimental setup used for this purpose.

TABLE II
SPECIFICATION OF ENGINE

Parameter	Specification
Engine type	4-stroke CI engine
Number of cylinders	One
Bore size	80mm
Stroke length	110mm
Cooling Type	Water cooling
Compression ratio	16
Rated power	5 HP@ 1500 rpm
Type of dynamometer	Rope dynamometer

A spring-connected rope dynamometer provides constant engine load. The spring span was manually loaded in 4 kg to 20 kg increments in gradations of 4 kg. The fuel measuring equipment had a burette to measure fuel usage. The fuel injector knob was attached to the engine's primary fuel line. At each loading situation, the time needed to consume 5 ml of fuel was noted using a stopwatch and utilized to calculate engine performance.

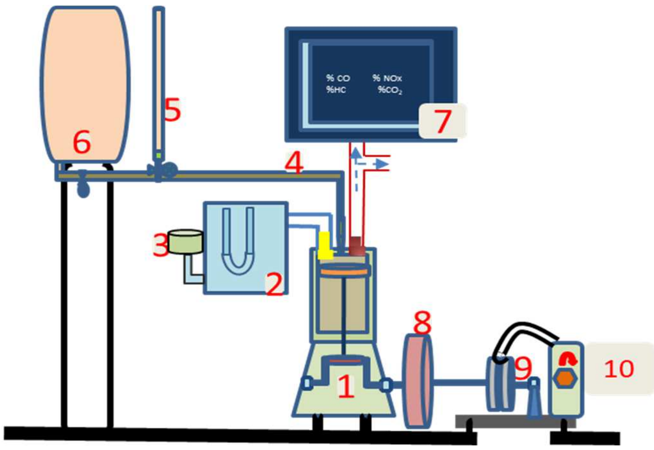


Fig. 3 Schematic diagram of the test engine (1 - Engine, 2 - Air-box with manometer,3 - Air filter,4 - Fuel Line, 5 - Fuel burette, 6 - Fuel Tank,7 - Exhaust Gas Analyzer, 8 - Flywheel, 9 - Eddy-current dynamometer,10 - Dynamometer Control)

Exhaust gas temperature is shown on the digital thermometer via a thermocouple attached to the exhaust pipe and is responsive to changes in load. It is factored into a formula that measures the engine's efficiency. The ambient air entered the engine's intake manifold via an air filter and air box coupled to a manometer. Regardless of load, the air pressure differential was converted into a water equivalent and used to determine engine performance. After testing the engine with different fuels, mathematical formulas were used to determine engine-specific fuel consumption, power, mean adequate pressure, and thermal efficiency. Different fuel samples were swapped, the fuel filter was cleaned, and trapped air in the engine was released.

III. Results and Discussion

As fossil fuels are used, CO_2, CO, NO_X, and other kinds of pollution continue to grow. The price difference and desire to save money motivate people to choose alternative fuels. Alternative fuels often include converting waste into usable energy. WTO is a waste-to-fuel alternative. By replacing diesel and biodiesel and mixing them with WTO, these concerns may be overcome.

A. Physicochemical Analysis

Table III outlines different characteristics of fuel specimens under study. Viscosity is an important characteristic of the fuel, and its value should be optimized to the greatest extent possible. When the viscosity is greater, the droplet size will be larger, resulting in poor mixture formation. As a result, this will cause a rise in energy consumption, a decline in performance, and a surge in soot emissions. Viscosity lower than the threshold limit causes insufficient lubrication in sliding sections of the fuel injection mechanism [61].

TABLE III
CHARACTERISTICS OF SAMPLES

Sample Labeling	Characteristics				
	Specific Gravity	Calorific value (MJ/kg)	Viscosity (mm^2/s)	Flash Point (^oC)	Fire Point (^oC)
D100	0.830	45.353	2.76	70	63
BD100	0.860	39.4592	4.25	135	136
WTO100	0.900	46.0845	7.36	140	145
WTO20D80	0.844	45.509	4.228	84	79.4
WTO30D70	0.851	45.5851	4.962	91	87.6
WTO20BD10D70	0.847	44.81	4.377	90.5	86.7
WTO30BD20D50	0.857	44.4	5.26	104	102.2

The viscosity of fuel is an important property that can affect its performance and efficiency in various applications. In the case of waste transformer oil (WTO) fuel-diesel blends, adding biodiesel can have a subtle impact on viscosity. Interestingly, experiments have shown that the viscosity of WTO10D90 is the lowest among the different blends tested. This suggests that using a higher proportion of waste transformer oil in the blend can lead to a more fluid fuel, which could benefit certain applications. In comparison with diesel, the fuel specimens consisting of palm oil biodiesel in the waste transformer oil fuel-diesel blends have a higher viscosity. This could be due to the differences in the chemical composition of biodiesel and diesel, which can affect their flow properties. Overall, the effects of adding biodiesel to waste transformer oil fuel-diesel blends on viscosity may be subtle, but they are still essential to consider. By understanding the viscosity properties of different fuels and blends, researchers and engineers can develop more efficient and effective fuels for various applications.

A diesel engine's fuel injectors use a volumetric measuring system. Higher densities have more energy per unit volume than lower ones. So, it can be attributed that with the rise in fuel density, the mass rate of injected fuel is also enhanced. Since the density of transformer oil is higher, a modest fraction of fuel is delivered. Palm biodiesel and blends of it have a higher specific gravity than diesel. Clean waste transformer oil has the highest specific gravity of all the samples. Density increases when the amount of used transformer oil in the blends increases. When palm biodiesel is added to blends of waste transformer oil and diesel, the density decreases.

Viscosity is a way to measure how hard it is for an oil to flow or how much friction it has inside. As the oil temperature goes up, its viscosity goes down, making it easier for it to flow [62]. When oil is injected into a C.I. engine, the higher the viscosity, the less it moves and spreads out. Because of this, the fuel does not burn completely, and carbon builds up on the injector nozzle and in the combustion chamber. Results show that used transformer oil has a higher viscosity than diesel. It has also been noted that the viscosity of a palm biodiesel-diesel mix may be lowered by adding waste transformer oil. This research shows that the viscosity of a palm biodiesel mix grows as its palm biodiesel content rises. Clean, used transformer oil had the highest viscosity of the fuels tested.

While palm biodiesel has a slightly lower calorific value than diesel, waste transformer oil has been discovered to have a more excellent calorific value. With more oxygen, palm biodiesel burns cleaner and has less oxidation potential. A fuel's combustion efficiency is enhanced when its structural oxygen content is high because more oxygen is evenly distributed throughout the fuel during burning. Therefore, biodiesel has better combustion efficiency than diesel. The flash point is a crucial criterion that must be considered when determining safety measures, which must account for potential fire threats and the transportation and storage of fuel. The moment when fuel vapors can be ignited is established by a combustion trigger outside the system. Because determining the “cetane number” is an expensive and lengthy operation, another association called the "Diesel Index" was conceived. This relationship is based on the quantity of hydrocarbons contained in the fuel and their specific gravity. n-Paraffin ignites better than aromatic compounds. Diesel Index serves Aniline Point. The aniline point is the minimal temperature at which gasoline and aniline become miscible, showing fuel aromaticity. A higher aromatic concentration lowers the aniline point. A higher cetane number makes it easier to light and heat up faster. Ignition lag and, hence, peak combustion pressure and temperature are functions of the fuel's cetane number in each engine. The weight proportion of each different kind of fuel or blend is mentioned in Table IV.

TABLE IV
CHEMICAL AND STRUCTURAL COMPOSITIONAL ANALYSIS OF TEST FUELS (THIS)

Sample labeling	Element (%)				
	Carbon (C)	Hydrogen (H)	Nitrogen (N)	Sulphur (S)	Oxygen (O)
D100	83.37	13.98	1.960	0.64	0.05
WTO100	83.949	13.013	2.385	0.60	0.053
BD100	76.39	11.849	0.000	0.000	11.76
WTO20D80	83.271	12.774	2.995	0.90	0.060
WTO30D70	81.893	12.756	4.440	0.85	0.061
WTO20BD10D70	80.830	12.576	5.433	1.09	0.062
WTO30BD20D50	77.269	11.464	5.301	5.90	0.066

Fig. 4 to Fig. 9 show the CHNS curve plot between millivolts and retention time. The values of 83.94% and 83.271% for the percentage of carbon found in samples WTO100 and WTO20D80, respectively, make it abundantly evident that these samples have a larger proportion of carbon. The sample BD100's carbon content value is much lower, coming in at 76.390%. The percentages of hydrogen found in the samples WTO100, WTO20D80, WTO30D70, and WTO20BD10D70, respectively, range from 13.013% to 12.774%, 12.756%, and 12.576%. The threshold hydrogen concentrations in samples BD100 and WTO30BD20D50 are 11.849% and 11.464%, respectively. The weights of the samples BD100, WTO100, WTO20D80, WTO30D70, WTO20BD10D70, and WTO30BD20D50 are respectively 2.181, 2.367, 2.736, 2.542, and 2.501 grams, whereas WTO30BD20D50 weighs 2.655 grams. According to this finding, the sample WTO100 has more carbon and hydrogen than the other samples.

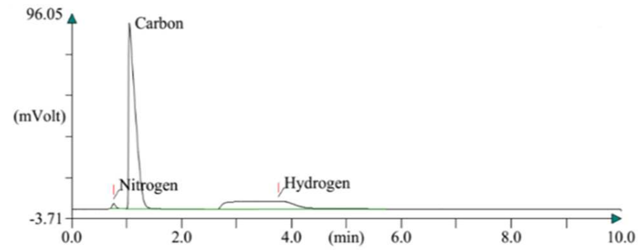


Fig. 4 CHN analysis of BD100

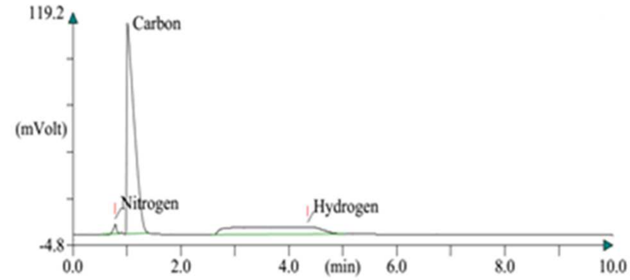


Fig. 5 CHN analysis of WTO20D80

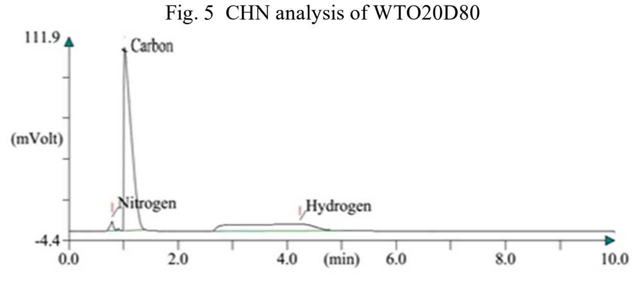


Fig. 6 CHN analysis of WTO30D70

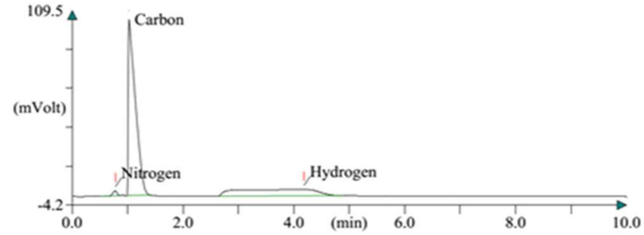


Fig. 7 CHN analysis of WTO100

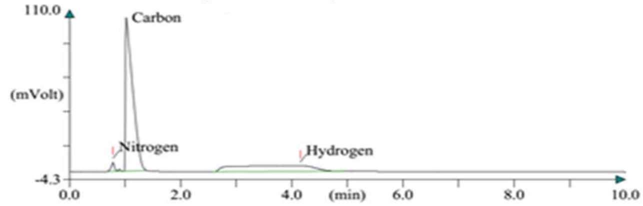


Fig. 8 CHN analysis of WTO20BD10D70

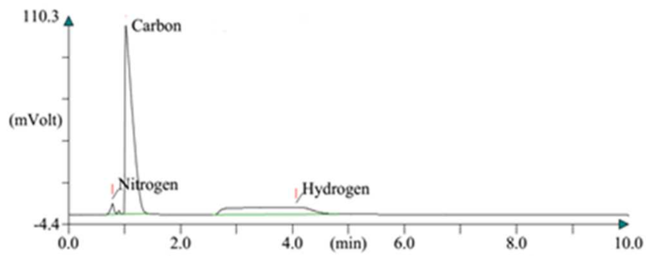


Fig. 9 CHN analysis of WTO30BD20D50

Fig. 10 to Fig. 16 display the FTIR (Fourier transform infrared spectroscopy) analysis of diesel and waste transformer oil (WTO) and their mixtures. The spectra of WTO and its mixtures are presented in FTIR.

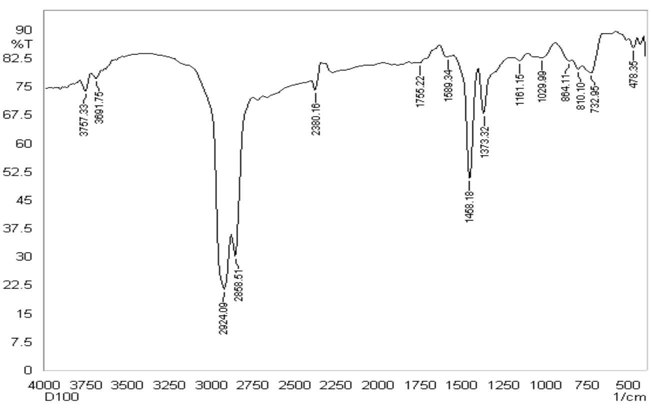


Fig. 10 FTIR analysis of D100

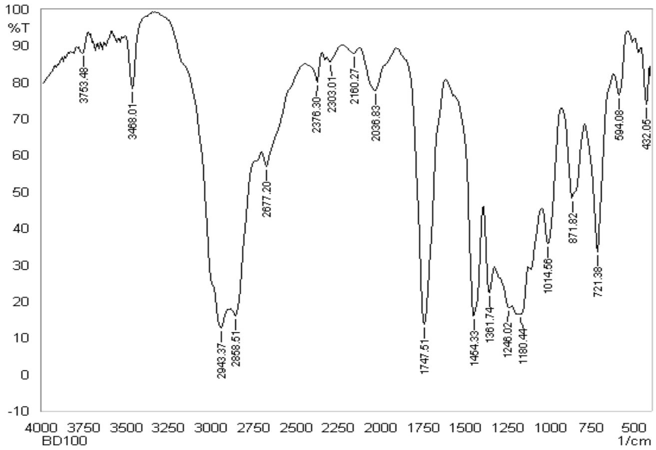


Fig. 11 FTIR analysis of BD100

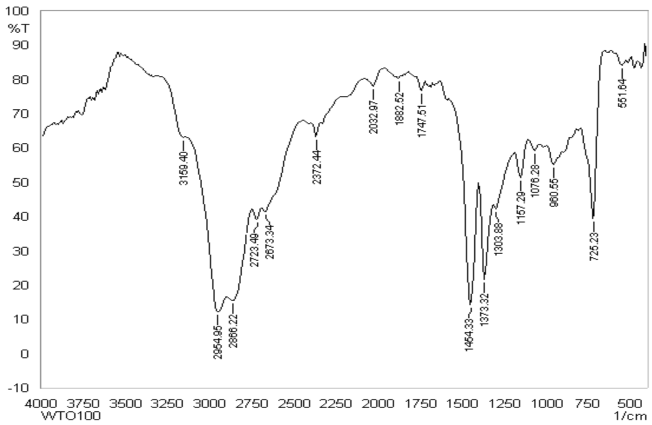


Fig. 12 FTIR analysis of WTO100

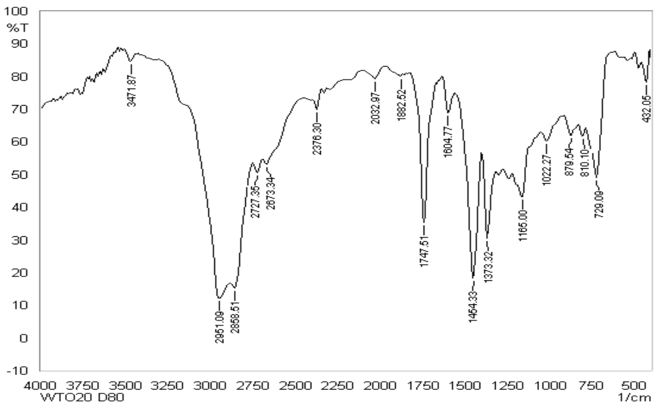


Fig. 13 FTIR analysis of WTO20D80

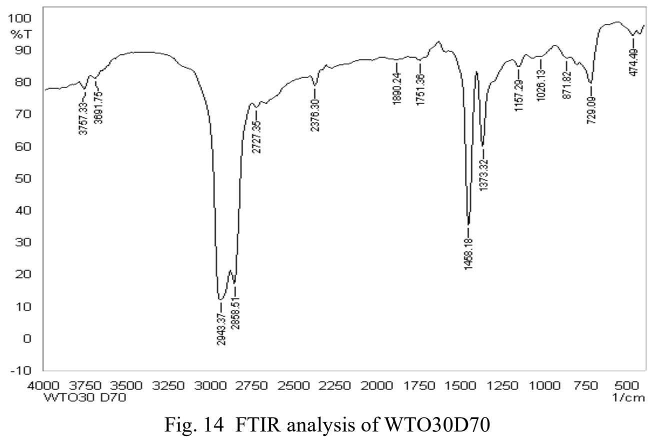


Fig. 14 FTIR analysis of WTO30D70

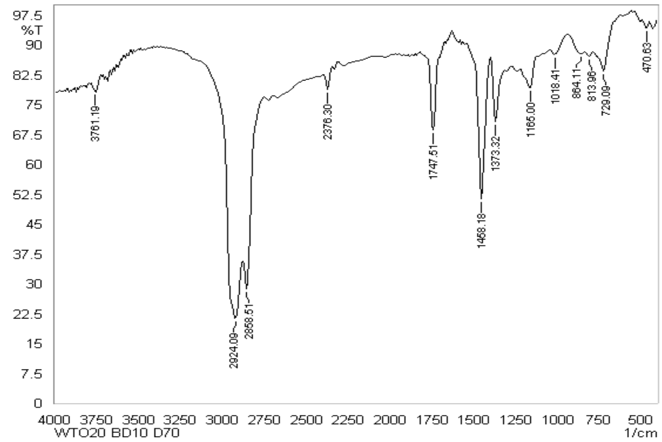


Fig. 15 FTIR analysis of WT020BD10D70

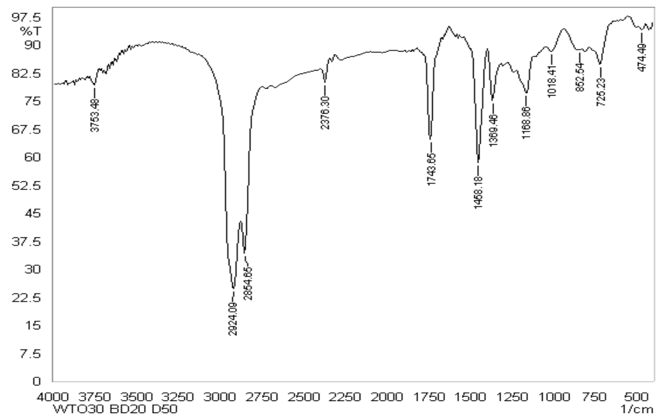


Fig. 16 FTIR analysis of WT030BD20D50

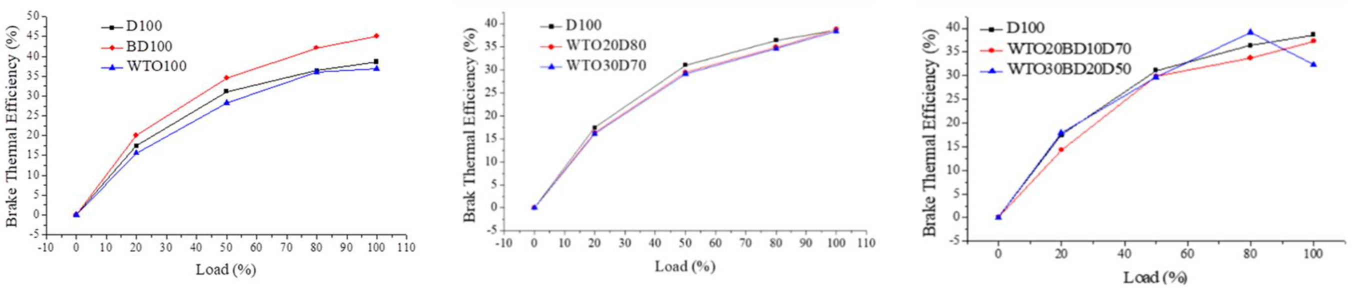
The FTIR incorporation is linked to the formation of covalent bonds; the information that it offers regarding the structural make-up of molecular compounds is exact. The FTIR analysis yielded findings illustrating a relationship between wavelength and transmittance percentage**.** These graphs provide details of the position of various bond vibrations, which may be differentiated by multiple types of vibration, such as stretching, distortion, bending, and so on. According to the FT-IR study of waste transformer oil (WTO), biodiesel, and its blends, the present chemicals include alkenes, aromatics, alcohols, phenols, and carboxylic acids, among other compounds. These compounds are comparable to the components that are found in diesel. Table V displays the results of FTIR analyses of the following oil/diesel mixtures.

B. Performance and Emission Testing

Fig. 17 depicts the deviation of thermal efficiency under varying loads. At a lower load condition of 20%, the brake thermal efficiencies of diesel, biodiesel, WTO100, WTO20D80, WTO30D70, WTO20BD10D70, and WTO30BD20D50 are, respectively, 17.43%, 20.01%, 15.64%, 16.30%, 16.14%, 14.3%, and 17.84%. Based on this comparison, it can be shown that biodiesel has a higher thermal performance of 3% than diesel at lower load conditions of 20%. The difference in efficiency becomes more obvious as the weight being carried rises. The brake thermal efficiency of WTO30BD20D50 is 32.32%, which is lower by 6% than diesel, whereas the brake thermal efficiency using biodiesel is 45%, which is higher by 7% than that of regular diesel. The comparison was made with a peak load of 100%.

TABLE V
TYPE OF VIBRATION OF ALL FUEL AND ITS BLENDS

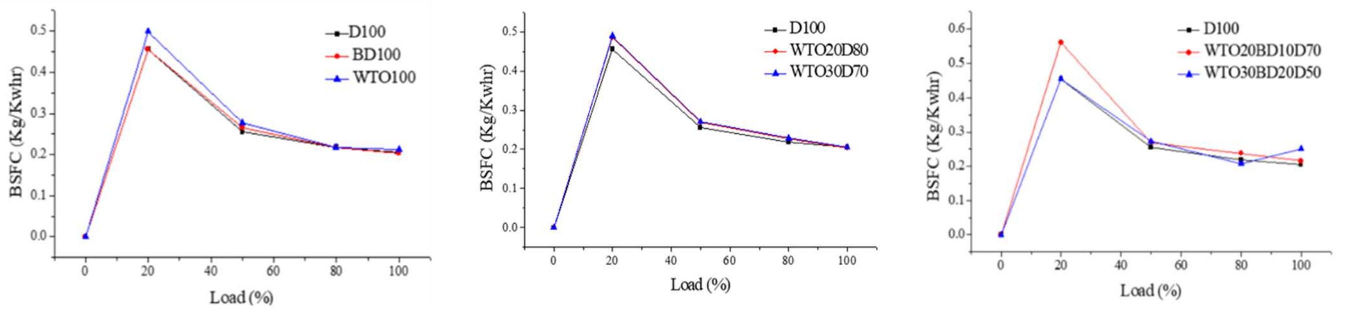
Sample Id	Type of Vibration					
	O-H Stretch	C-H Stretch	C≡C, C≡N Stretch	N-H bending, C=C stretch, C=O stretch	N=O stretch	C=O stretch, Carbonates
D100	3757, 3691	2924, 2858	2380	1755	1589,1458, 1373	478
BD100	3753, 3468	2943, 2858	2376,2303	1747	1454, 1361, 1246	432
WTO100	3159	2954, 2866	2372	1747	1454, 1373, 1303	551
WTO20D80	3471	2951, 2858	2376	1747	1604, 1454, 1373	432
WTO30D70	3757, 3691	2943, 2858	2376	1751	1458, 1373	474
WTO20BD10D70	3761	2924, 2858	2376	1747	1458, 1373	470
WTO30BD20D50	3753	2924, 2854	2376	1743	1458, 1369	474
Compound group present	Phenol	Carboxylic acid, alcohol	Alkynes/Aromatic	Alkenes/Aromatic aldehyde and ketone	Nitro compounds	Carbonates



(a) (b) (c)

Fig. 17 (a) BTE vs. load for Base fuels, (b) BTE vs. load Base fuels and WTO with Diesel blends, (c) BTE vs. load WTO with biodiesel and Diesel blends

The amount of fuel consumed for unit break power is referred to as brake-specific fuel consumption (BSFC). It is also known as "power-specific fuel consumption" [63]. It measures how much energy an engine wastes in comparison to how much energy it produces [64]. BSFC is measured in kilowatt-hours. Fig. 18 shows that the BSFC line for diesel and biodiesel is close together. This suggests that a lower quantity of diesel must be spent to get the same level of braking power as WTO100, WTO20D80, WTO30D70, and WTO20BD10D70.

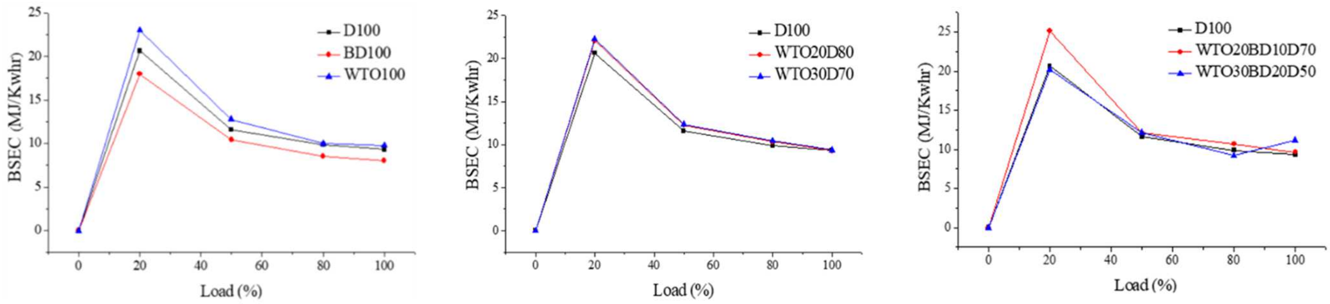


(a) (b) (c)

Fig. 18 (a) BSFC vs. load for Base fuels; (b) BFSC vs. load Base fuels and WTO with Diesel blends; (c) BFSC vs. load WTO with biodiesel and Diesel blends

According to what can be seen in the figure, the BSFC line for each different kind of fuel or mix begins at the exact location on the BSFC axis. The primary specific fuel consumption is 0.455 kg/Kwh at 20% load. Except for WTO30BD20D50, all fuel and blends have the same BSFC at a peak load of 100%, which is 0.205 kg/Kwh. However, the BSFC for WTO30BD20D50 is 0.250 kg/Kwh. Samples D100, BD100, WTO100, and WTO30BD20D50 all have BSFC lines that cross at around 80% of load condition, but beyond that, WTO100's BSFC line is elevated above those of D100 and BD100. It indicates combustion inefficiency and poor flame propagation within the combustion chamber.

Power-specific energy consumption is another name for brake-specific energy consumption (BSEC). Energy consumption divided by power, with a kilowatt unit per hour, is the method for determining brake-specific energy consumption. Using the results shown in Fig. 19, it can be seen that the BSEC of biodiesel and WTO30BD20D50 are the lowest in the obtained plot, indicating that biodiesel requires less energy to achieve the same braking power as WTO100, WTO20D80, WTO30D70, and WTO20BD10D70.

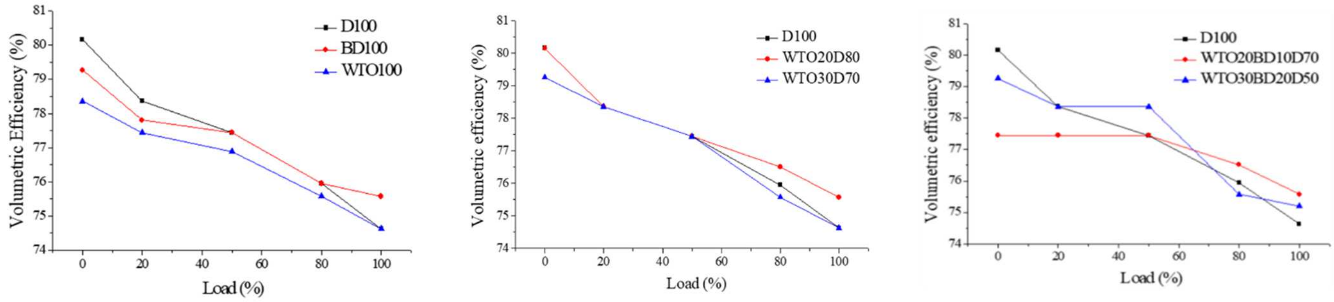


(a) (b) (c)

Fig. 19 (a) BSEC vs. load for Base fuels; (b) BSEC vs. load Base fuels and WTO with Diesel blends; (c) BSEC vs. load WTO with biodiesel and Diesel blends

At 20% load, the BSEC axis for all fuel types and blends begins at the same place, at 17.98 MJ/Kwh. As the load increased from 0 to 100%, BSEC decreased for all fuel types and mixes. The BD100 has the lowest BSEC (maximum load, 20 kg) of any fuel or blend type, at 8 MJ/Kwhr. WTO30BD20D50, on the other hand, has a BSEC of 11.14 MJ/Kwhr at full load. The results demonstrated a decline in BSEC with increasing load, except for the WTO30BD20D50 after 80% load.

One way to evaluate a cylinder's performance is by calculating its volumetric efficiency, the airflow rate at the input condition divided by its swept volume. Fig.s 20 shows that the volumetric efficiency of all fuel types and mixes is nearly the same under no-load conditions, at around 80%. As the load grows, volumetric efficiency drops for every fuel and blend combination [65].

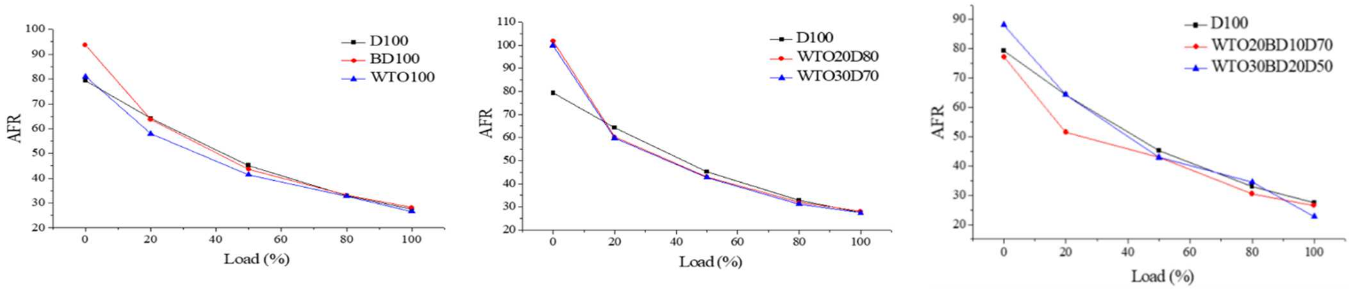


(a) (b) (c)

Fig. 20 (a) Volumetric efficiency vs. load for Base fuels; (b) Volumetric efficiency vs. load Base fuels and WTO with diesel blends; (c) Volumetric efficiency vs. load WTO with biodiesel and diesel blends

Under full loading conditions, the volumetric efficiency of all fuel types drops to 75%. Fig. 20 shows that WTO100 and WTO30D70 have lower volumetric efficiency than diesel fuel at a 20% load condition, and Fig. 20 shows that WTO20BD10D70 and WTO30BD20D50 also have lower volumetric efficiency than diesel. The WTO20BD10D70 outperforms the diesel WTO30BD20D50 in volumetric efficiency with loads up to 12 kg.

The air's mass flow rate corresponding to fuel's mass flow rate defines the air-fuel ratio (AFR). AFR is also described as the ratio of air mass to fuel mass, or how much air the engine uses for every unit of fuel. The AFR vs. load percentage of various fuels and mixes is shown in Fig. 21. At idle, WTO20D80 has the highest AFR compared to other fuels and mixtures. When the load increases, the air-fuel ratio (AFR) drops for all fuels and mixtures.

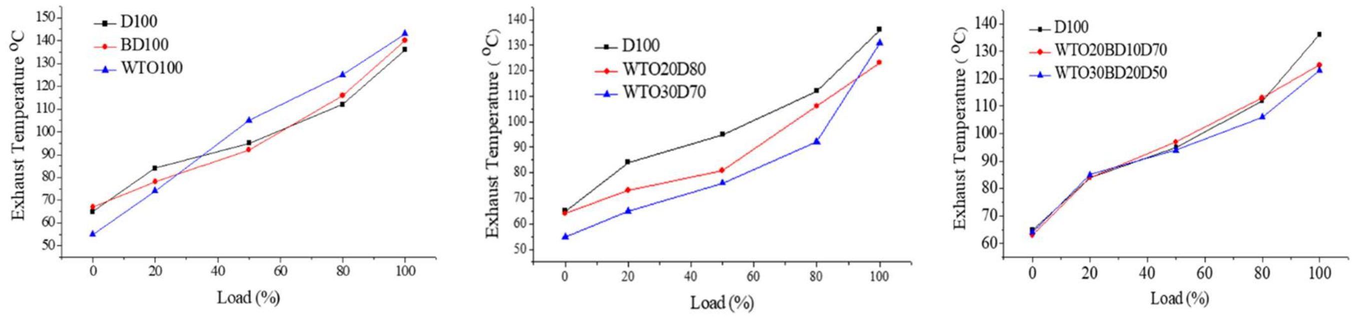


(a) (b) (c)

Fig. 21 (a) Air fuel ratio vs. load for Base fuels; (b) Air fuel ratio vs. load Base fuels and WTO with Diesel blends; (c) Air fuel ratio vs. load WTO with biodiesel and Diesel blends

At a peak load of 100%, the AFRs for D100, BD100, WTO100, WTO20D80, WTO30D70, WTO20BD10D70, and WTO30BD20D50 are 27.4, 28.2, 26.5, 28, 27.4, 26.5, and 22.63, indicating that larger loads result in higher fuel consumption of all types. The WTO20D80 has the lowest fuel usage at idle, while the WTO20BD10D70 has the most. The WTO20D80 and the WTO30BD20D50 use the least fuel while operating at low loads and the most when operating at high loads, respectively.

The gas released at the exhaust is referred to as the exhaust temperature. Thermocouple probes are used to make the measurements [66]. The exhaust temperature of the WTO100 is less than that of the D100 and BD100, and when the load grows, so does the exhaust temperature of the WTO100. Fig. 22a shows that the BD100 has a greater exhaust temperature than diesel. Fig. 22b demonstrates that the blends WTO20D80 and WTO30D70 have a lower exhaust temperature than D100 under each load scenario. Fig. 22c shows that the exhaust temperatures of D100, WTO20BD10D70, and WTO30BD20D50 all begin around the same position and are similar up to a load of 10 kg but then rise above those of WTO30BD20D50 after the load has been increased. When the CI engine is under more load, the exhaust temperature of any given fuel or blend rises.

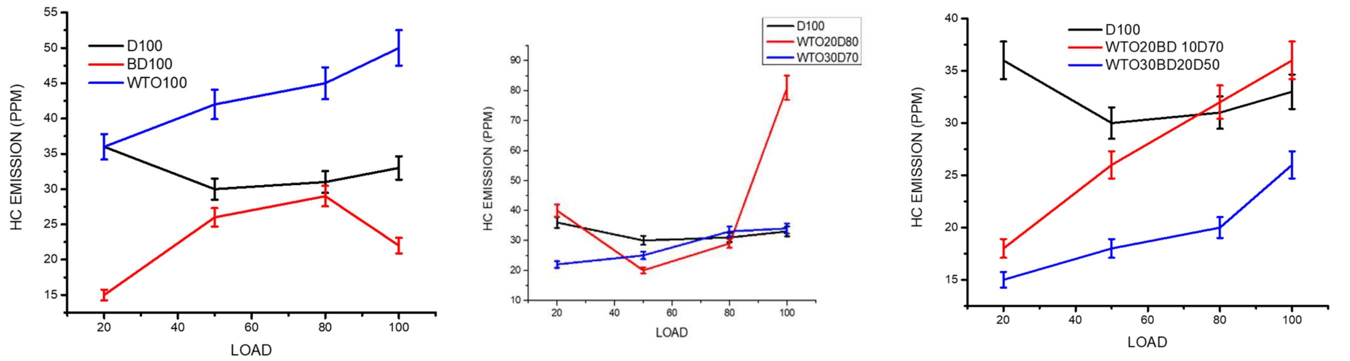


(a) (b) (c)

Fig. 22 (a) Exhaust temperature vs. load for Base fuels; (b) Exhaust temperature vs. load Base fuels and WTO with Diesel blends; (c) Exhaust temperature vs. load WTO with biodiesel and Diesel blends

C. Features of emission

While operating at partial loads, hydrocarbon (HC) emissions are lower for all of the fuels under investigation, but these emissions tend to grow when operating at increasing loads [67]. This is because the engine is working at a higher equivalence ratio, resulting in less oxygen availability [68]. The deviation of HC emission with load is depicted in Fig. 23.

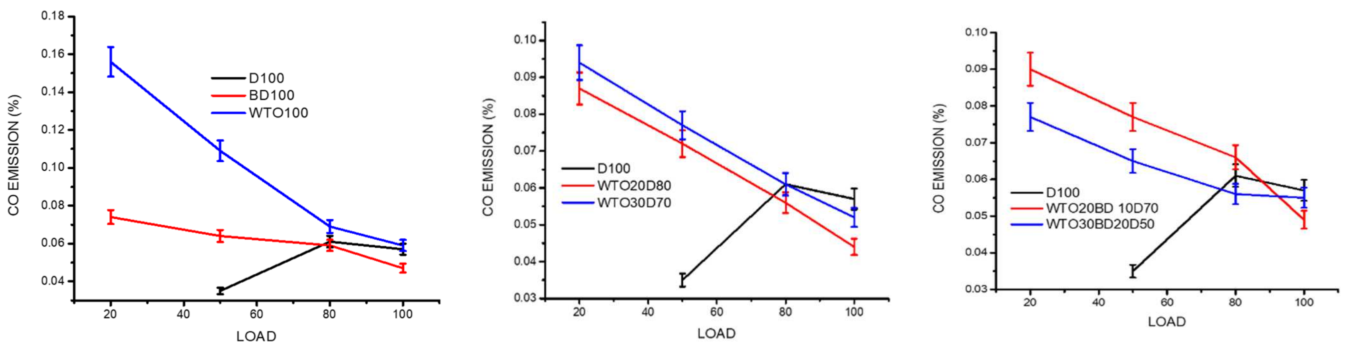


(a) (b) (c)

Fig. 23 (a) Hydrocarbon emission vs. load for Base fuels; (b) Hydrocarbon emission vs. load Base fuels and WTO with diesel blends; (c) Hydrocarbon emission vs. load WTO with biodiesel and diesel blends

From Fig. 23, the highest HC emission is found in the case of raw waste transformer oil, whereas it is lower in the case of WTO-diesel and WTO-BD-diesel blends. The lowest HC emission is seen in the case of WTO30BD20D50. In the case of WTO30BD20D50, there is a decrease of 13% and 48% HC emission at maximum load when compared to diesel and raw WTO.

CO emissions are depicted with load for each test fuel, as plotted in Fig. 24. Colorless, odorless, and very poisonous, carbon monoxide (CO) is a gas you should avoid being around. Carbon monoxide (CO) is seen as an understandable emission and a symbol of wasted chemical energy. It is created by burning a fuel with a high equivalency ratio in an internal combustion engine [69]. Not all the fuel is burned, and the carbon is converted to carbon monoxide if there isn't enough oxygen (CO).

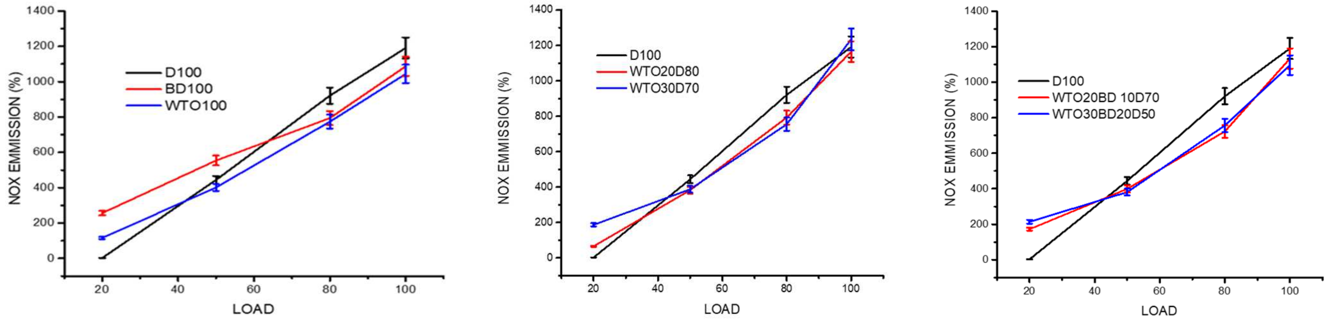


(a) (b) (c)

Fig. 24 (a) Carbon Monoxide emission vs. load for Base fuels; (b) Carbon Monoxide emission vs. load Base fuels and WTO with Diesel blends; (c) Carbon Monoxide emission vs. load WTO with biodiesel and Diesel blends

It is increasing the load results in lower CO emissions from all fuels used. This might be because, as the load rose, more fuel was delivered into the cylinder, causing its temperature to rise from its low point at minimum load [70]. As more fuel could be burned at higher temperatures with less carbon monoxide being produced, the engine's efficiency improved. CO emissions from a diesel engine are affected by the fuel's physicochemical properties, the A/F ratio, and the operating temperature of the engine [71]–[73]. From Fig. 24a, it can be observed that the CO emission is the highest. In the case of raw WTO, the CO emission is significantly higher at lower loading conditions. From Fig. 24b, the lowest CO emission is observed in the case of WTO20D80. With the addition of biodiesel in the WTO-diesel mix, as shown in Fig. 24c, the lowest CO emission is found in the case of WTO20BD10D70. In fact, for the WTO20BD10D70, the CO emission is observed to be at a minimum with all the fuel samples except pure biodiesel BD100. The CO emission in the case of WTO20BD10D70 is 14% and 17% less than diesel and raw WTO, respectively.

Fig. 25 depicts the deviation in NOx emission with load. Very high nitrogen oxides (NOx) levels may be detected in vehicle exhaust, perhaps exceeding 2,000 ppm. Nitrogen oxides, abbreviated NOx, consist of various nitrogen-oxygen combinations. Because of its propensity to react and produce ozone, NOx is very undesirable [74]. Regarding photochemical smog, this is a significant cause for alarm. Vehicle emissions react with ambient air to create smog. NOx dissociates into NO and Oxygen and then generates Ozone [75]. Yearly loss of crops is attributed to the ozone layer, widespread at lower atmospheric levels and particularly hazardous to plants. High temperatures are necessary for the reaction between nitrogen and oxygen; hence, an abundance of oxygen and a warm environment are the two main contributors to NOx production [76]. Emissions of nitrogen oxides (NOx) are very fuel-specific and are affected by factors such as droplet size, penetration rate, spray properties, evaporation rate, and air mixing [77]–[79]. NOx production may be influenced by any of these factors [80]. The graph demonstrates that NOx emissions result from increased engine load.

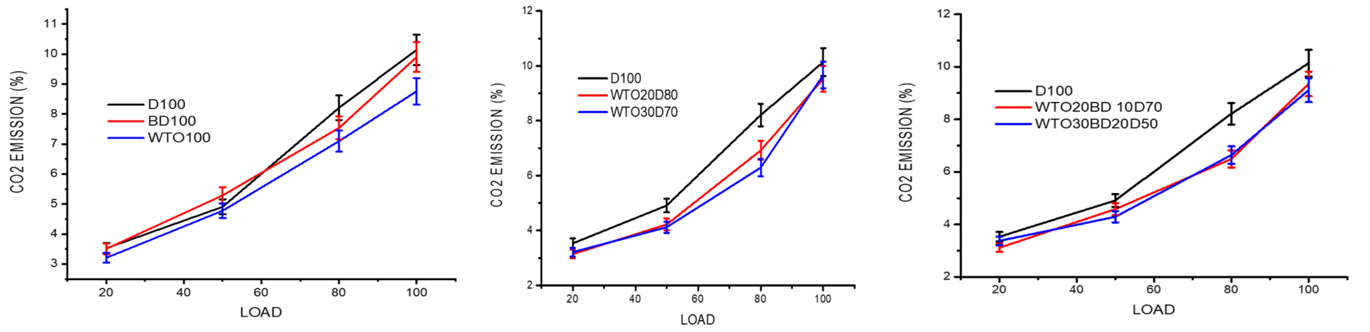


(a) (b) (c)

Fig. 25 (a) NOx emission vs. load for Base fuels; (b) NOx emission vs. load Base fuels and WTO with Diesel blends, (c) NOx emission vs. load WTO with biodiesel and Diesel blends

From Fig. 25a, the highest NOx emission is observed with pure diesel. From Fig. 25b, the lowest NOx emission is observed if so WTO20D80. From Fig. 25c, the lowest NOx emission is found with WTO20BD10D70, but at the maximum loading condition, the NOx emission of WTO30BD20D50 is observed to correspond to all the blended fuel samples. At the maximum loading condition, the NOx emission of WTO20BD10D70 and WTO30BD20D50 are observed to be 5% and 8% lower than pure diesel, respectively.

Fig. 26 illustrates the deviation of CO_2 emissions against different load conditions for fuel samples. From Fig. 26, it is perceived that the emission of CO_2 increases with load, as was expected. Combustion produces CO_2, which may be present in the air. Hydrocarbon fuel would only burn to produce CO_2 water vapor in a perfect combustion process [81]. From Fig. 26a, the lowest CO_2 emission is observed with raw WTO and the highest in the case of pure diesel. From Fig. 26b, the CO_2 emission is more with WTO20D80 than WTO20BD10D70. From Fig. 26c, the CO_2 emission is more with WTO20BD10D70 than with WTO30BD20D50. Diesel has produced higher CO_2 emissions than others.



(a) (b) (c)

Fig. 26 (a) Carbon Dioxide emission vs. load for Base fuels; (b) Carbon Dioxide emission vs. load Base fuels and WTO with Diesel blends; (c) Carbon Dioxide emission vs. load WTO with biodiesel and Diesel blends

IV. Conclusion

According to the investigation, the specific gravity of raw WTO is the highest among all the fuel samples, and the inclusion of biodiesel and diesel in the raw WTO reduces the specific gravity. The flash point of the raw WTO and WTO-biodiesel blends is significantly higher or even higher than the raw biodiesel. So, the WTO blends are safe in terms of storage and transportation of fuel. Raw WTO's calorific value and viscosity are marginally higher than raw biodiesel and regular diesel.

The CHN analysis shows that the raw WTO and their blends have almost similar carbon content but slightly higher sulfur content than diesel. The FTIR analysis indicates that the WTO and their blends have some common similar functional groups like alkanes, alkenes, aromatics, alcohols, phenols, carboxylic acids, etc. This study suggests that the WTO and its blends may be utilized as substitute fuels for CI engines.

As per the performance analysis, it is found that the brake thermal efficiency (BTE) using palm oil biodiesel is highest at partial and full loading conditions. At full loading conditions, the thermal efficiency of raw WTO is recorded as 4.54% less than diesel. The BSFC of raw biodiesel is observed to be almost similar to diesel, whereas the BSFC of raw WTO is 3% higher than diesel at full load conditions. The blends of WTO and diesel show almost similar BSFC diesel; the WTO20BD10D70 and WTO30BD20D50 have slightly higher BSFC, about 4.73% and 22.02%, respectively, corresponding to WTO, biodiesel, and diesel blends. At total loading, the BSEC for WTO20D80 is identical to that of diesel. However, those for WTO20BD10D70 and WTO30BD20D50 are significantly higher than those for diesel at 3.47% and 19.46%, respectively. The exhaust gas temperature (EGT) has increased with the load. At full loading conditions, the EGT of raw WTO is recorded highest, followed by raw biodiesel. The EGT in the case of WTO20BD10D70 and WTO30BD20D50 is lower by 8% and 9.55%, respectively, than diesel.

Among all the fuels tested, at full loading conditions, the HC emission of raw biodiesel is recorded as the lowest, whereas raw WTO is found to be the highest. The HC emission in WTO20D80 and WTOD70 is slightly higher than diesel, whereas in the case of WTO20BD10D70, it is 20% higher than diesel. The CO emission of raw biodiesel is found to be the lowest, whereas the CO emission of WTO20BD10D70 and WTO30BD20D50 is seen to be 14% and 8.7% lower than diesel—the NOx emission increases with load. At full loading, the NOx emission for raw WTO is found to be lowest, whereas for WTO20BD10D70 and WTO30BD20D50, it is observed to be lower by 4.78% and 7.94%, respectively, than diesel. CO2 emission increases with load. CO2 emission is highest and lowest at full loading conditions with diesel raw WTO. The CO2 emission of WTO20BD10D70 and WTO30BD20D50 is lower by 9.6% and 12.73%, respectively, than diesel.

The above findings recommend that the diesel engine can operate when fueled with WTO blends, even with the raw WTO, without any modification. Considering the overall analysis of WTO blends, including performance and emission, except for the higher HC emission in the case of the sample coded with WTO20BD10D70, it shows a satisfactory result. The brake thermal efficiency (BTE) of WTO20BD10D70 is almost similar to diesel fuel; its BSFC and BSEC are observed to be higher by 4.73% and 3.46%, respectively, than diesel. Its exhaust gas temperature (EGT) is 8% lower than diesel. Its volumetric efficiency is also found to be higher than diesel. The HC emission using WTO20BD10D70 as fuel is 20% higher than diesel, but the CO and NOx emissions are lower by 14% and 4.75% than diesel. Thus, the sample coded with WTO20BD10D70 can be recommended as an alternative to regular diesel in the CI engine.

Nomenclature

BSEC	Brake-specific energy consumption
BSFC	Brake-specific fuel consumption
BTE	Brake thermal efficiency
CFPP	Cold filter plugging point
CONS	Carbon Hydrogen Nitrogen Sulphur
CO	Carbon monoxide
CO_2	Carbon dioxide
CN	Cetane number
EDIT	Exhaust gas temperature
FAIR	Fourier transforms infrared spectroscopy
GC-MS	Gas chromatography-mass Spectrometer
HC	Hydrocarbon
NOx	Nitrogen oxide
PM	Particulate matter
PP	Pour point
PPM	Parts per million

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